Turbulence Model Validation for Complex Mixing Scenarios

Bertrand Rollin, CCS-2;
Nicholas A. Denissen,
Jon M. Reisner,
Malcolm J. Andrews, XCP-4;
Jimmy Fung, XCP-1

Computing requirements for simulating complex multi-physics flows are such that Reynolds averaged Navier-Stokes (RANS) models will remain the community's chosen workhorse for years to come. Within applications of interest to LANL, such as compressible mixing, the Besnard Harlow Rauenzahn (BHR) RANS models are being utilized within Advanced Simulation and Computing (ASC) codes. Specifically, the present work examines the ability of the BHR-2 turbulence model to simulate Rayleigh-Taylor mixing and bulk interface motions of two fluids driven by gravity within a tilted rig experiment. We present here the results from simulations using the BHR-2 model and compare them to available experimental and Implicit Large Eddy Simulation (ILES) results. These comparisons are intended to demonstrate the utility of the BHR-2 model to accurately predict various aspects of compressible turbulent mixing.

Turbulence and turbulent mixing are ubiquitous in nature and engineering applications. Whether considering numerical weather prediction, combustion efficiency in a scramjet engine, or performance of an Inertial Confinement Fusion (ICF) capsule, the effects of turbulence cannot be disregarded. However, the multi-scale and 3D nature of turbulent flows is such that turbulence modeling, as opposed to direct numerical simulation of a given flow field, is the only practical approach when studying full-scale engineering problems. In particular, RANS models remain the standard tool for a wide variety of complex, multi-physics applications.

To address the range of applications of interest at LANL, the BHR family of compressible turbulent mix models were developed and then implemented in LANL ASC models such as xRage [1]. The present work uses one member of the BHR family, BHR-2, which solves transport equations for kinetic energy, K, turbulence length scale, L, turbulent mass-flux velocity, $\boldsymbol{a}_i$, and density-specific volume correlation, b. BHR-2 has been demonstrated for canonical turbulent flows such as Kelvin-Helmholtz, Rayleigh-Taylor, and Richtmyer-Meshkov [4] where, on average, mixing is 1D. However, in many problems of interest, there can be significant curvature of the interface as well as dynamic interface movement. How BHR-2 handles these effects, both the influence of the turbulence on the bulk motion of the interface, and vice versa, is essential for the tilted-rig experiment shown in this paper, as well as within more complex applications of interest to LANL.

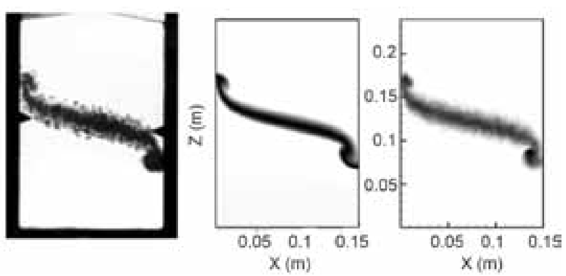

Fig. 1. Mixing region at t=45 ms from experiment (left), a LANL hydrocode, FLAG, with BHR-2 modeling (middle), and ILES (right).

Tilted-rig experiments were originally run in the 1980s and early 1990s by Smeeton and Youngs [5], Andrews and Spalding [6,7], and Ptitzyna et al. [8]. In these experiments, a tank filled with a light fluid above a heavy fluid is tilted a few degrees off the vertical causing a slanted interface. Upon acceleration of the tank by rocket engines and a resulting reversal of gravity, large-scale overturning motion quickly commences producing rising and falling plumes at the side edges of the tank and Rayleigh-Taylor-driven mixing at the center of the tank.

Figure 1 shows comparisons between the photograph of the actual experiment [5], the RANS, and ILES simulations at t = 45 ms. Close inspection of this figure reveals that the RANS simulation is able to reproduce with good accuracy the bubble (right-hand-side fluid structure) and spike (left-hand-side fluid structure) penetration distance as well as their overall shape, but slightly under-predicts the mixing layer size. These comparisons reveal that the flow dynamics displayed by the ASC hydrocode coupled to the BHR-2 model is consistent with the flow dynamics observed in the experiments and ILES.

Further assessment of the model requires comparisons between the turbulence model variables as predicted by BHR-2 and inferred from the ILES. The first quantity of interest is the turbulence kinetic energy, K, as it is the most affected by the motion of the interface. Figure 2 shows the distribution of K as predicted by RANS modeling and ILES at t=45 ms. Both kinetic energy contours show identical dominant features. Local maxima of K can clearly be identified at the tip of the bubble and spike. The widening and increase in intensity of K when moving toward the bubble side is well captured by the RANS simulation as well as the asymmetry of the distribution. Next, the turbulent mass-flux velocity–a key quantity in compressible turbulence as it is the primary production

For more information contact Bertrand Rollin at bertrand@lanl.gov.

Funding Acknowledgments
DOE, NNSA, Advanced Simulation and Computing Program

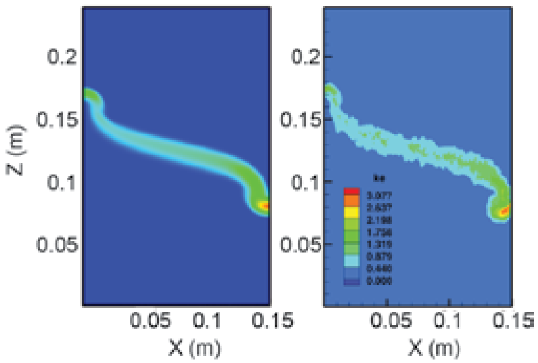

Fig. 2. Distribution of turbulent kinetic energy, K, as predicted by a LANL hydrocode, FLAG, with BHR-2 (left) and ILES (right) at t=45 ms.

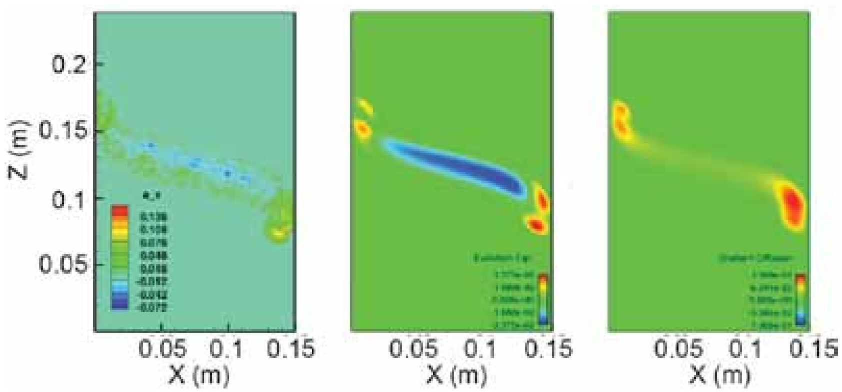

Fig. 3. Distribution of horizontal mass flux, $\mathbf{a}_x$*, as predicted by ILES (left), a LANL hydrocode, FLAG, with BHR-2 (middle), and a LANL hydrocode (FLAG) with a classic K/L (two-equation) turbulence model (right) at time t=45 ms.*

term for turbulent kinetic energy–is compared against corresponding results from a commonly used two-equation RANS model. As evident in Fig. 3, BHR-2 is able to predict the negative (counter-gradient) horizontal turbulent mass-flux velocity in the center of the mixing layer seen in ILES, contrary to the two-equation turbulence model. This finding suggests the better suitability of the four-equation BHR-2 model over two-equation models for handling complex mixing scenarios.

Key findings of the BHR-2 turbulent-mix model's validation for problems with dynamic interfaces have been presented. The BHR-2 model can efficiently predict a variety of turbulence quantities including turbulent kinetic energy, turbulent mass-flux and density-specific volume correlation (not shown). The model does not adversely affect the mean interface motion, and accurately captures differences in turbulence intensity along the moving interface. Detailed analysis of this work and future perspectives can be found in Denissen et al. [9] and Rollin et al. [10].

[1] Besnard, D. et al., *LANL Technical Report* "Turbulence Transport Equations for Variable-Density Turbulence and thier Relationship to Two-Field Models." LA-12303-MS (1992).

[2] Banerjee, A. et al., *Phys Rev E* **82**, 046309 (2010).

[3] Schwarzkopf, J.D. et al., *J Turbulence* **12**, N49 (2011).

[4] Stalsber-Zarling, K. and Gore, R.A., *"The BHR2 Turbulence Model: Incompressible Isotropic Decay, Rayleigh-Taylor, Kelvin-Helmoholtz and Homogneous Variable Density Turbulence."* LANL Technical Report LA-UR–11-04773 (2011).

[5] Smeeton, V.S. and D.L. Youngs, *"Experimental Investigatin of Turbulent Mising b y Rayleigh-Taylor Instability Part 3."* AWE Report No. O 35/87 (1987).

[6] Andrews, M., *Ph.D. Thesis*, "Turbulent Mixing by Rayleigh-Taylor Instability." London University (1986).

[7] Andrews, M. and Spalding, D., *Phys Fluids A* **2**(6), 322-327 (1986).

[8] Ptitzyna N.V. et al., *Proceedings 4th IWPCTM*, 729-743 (1993).

[9] Denissen N.A. et al., Proceedings *43rd AIAA Fluid Dynamics Conference and Exhibit*, in preparation (2013).

[10] Rollin, B. et al., Proceeding *IMECE 2012*, IMECE2012-93094 (2012).